

Response to overburden pressure of an HDPE pipe pulled in place by pipe bursting

B.M. Lapos, R.W.I. Brachman, and I.D. Moore

Abstract: Measurements of vertical and horizontal pipe deflections are reported for a high-density polyethylene (HDPE) pipe experiencing an increase in vertical pressure after being pulled in place using pipe bursting techniques. Three tests were conducted to measure the diameter change of a 165 mm outside diameter HDPE pipe after replacing an intact clay pipe with an external diameter of 184 mm backfilled with a poorly graded dense sand. A fourth test measured the response of the HDPE pipe after replacing an intact clay pipe with an external diameter of 128 mm. Variable pipe deflections were measured in each test, which depended on the interactions among the broken clay pipe fragments surrounding the HDPE pipe. The orientation of the clay fragments controls whether the increase in vertical pressure is transferred immediately to the HDPE pipe. In some cases, the fractured clay pipe produced a structural ring encasing the HDPE pipe, thus providing additional hoop strength. Two of the replacement tests did not record diameter changes until 100 kPa because of the interaction amongst the clay fragments. The upsized test and one replacement test recorded diameter changes from a vertical pressure of 20 kPa, because there were no interactions observed among the clay fragments.

Key words: pipe bursting, trenchless technology, plastic pipe, pipe deflections.

Résumé : On fait rapport des mesures de déflexions horizontales et verticales d'un tuyau en « high-density polyethylene » (HDPE) subissant une augmentation de pression verticale après avoir été tiré en place au moyen des techniques d'éclatement de tuyau. Trois essais ont mesuré un changement de diamètre de 165 mm du diamètre extérieur du tuyau HDPE après avoir remplacé un tuyau en terre cuite intact ayant un diamètre extérieur de 184 mm rempli de sable dense ayant une granulométrie dispersée, alors qu'un quatrième essai a mesuré la réaction d'un tuyau en HDPE après avoir remplacé un tuyau intact en terre cuite avec un diamètre extérieur de 128 mm. Des déflexions variables du tuyau ont été mesurées dans chaque essai, dépendant des interactions entre les fragments de terre cuite des tuyaux broyés entourant le tuyau de HDPE. Que l'accroissement de la pression verticale soit transférée immédiatement ou non sur le tuyau de HDPE dépend de l'orientation des fragments de terre cuite. Dans certains cas, les fragments de tuyau en terre cuite produisent un anneau structurel enveloppant le tuyau de HDPE et fournissant un effet de résistance additionnelle en circonférence. Deux des essais de remplacement n'ont pas enregistré de changements de diamètre jusqu'à 100 kPa à cause de l'interaction des fragments de terre cuite. L'essai à plus grand diamètre et un essai de remplacement ont enregistré des changements de diamètre à partir de pressions verticales de 20 kPa parce qu'aucune interaction entre les fragments de terre cuite n'a été observée.

Mots-clés : éclatement de tuyau, technologie sans tranchée, pieu élastique, déflexions de tuyau.

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Introduction

Pipe bursting is a construction technique where a deficient buried pipe (either structurally deteriorated or hydraulically undersized) is replaced with a new pipe without the need for a cut-and-cover excavation along the pipeline. The new replacement pipe is pulled into place following a bursting head that breaks and displaces the original (or replaced) pipe as shown in Fig. 1.

Ground displacements and pulling forces associated with pipe bursting have been previously examined using theoretic-

cal techniques (Rogers and Chapman 1998; Fernando and Moore 2002) and physical testing (Chapman and Rogers 1991; Lapos et al. 2004). However, there is a paucity of data on the structural response of a pipe pulled into place via pipe bursting when that new pipe is subjected to additional vertical pressure (e.g., construction of an overlying embankment). The physical response of a buried pipe when subjected to increases in vertical pressures is normally a function of the stiffness of the pipe and the soil and the interactions between the two (e.g., Hoeg 1968, Moore 2001). For a pulled-in-place pipe, it may be hypothesized that expansion and contraction of the soil cavity during installation and possible interactions with remaining fragments of the original pipe also influence the structural response of the new pipe.

The objective of this paper is to quantify the response of a high-density polyethylene (HDPE) pipe installed by pipe bursting and then subjected to increasing overburden pressure. Measured pipe deflections and other observations are reported from five experiments where an HDPE pipe (outside diameter, OD, equal to 165 mm and wall thickness, t ,

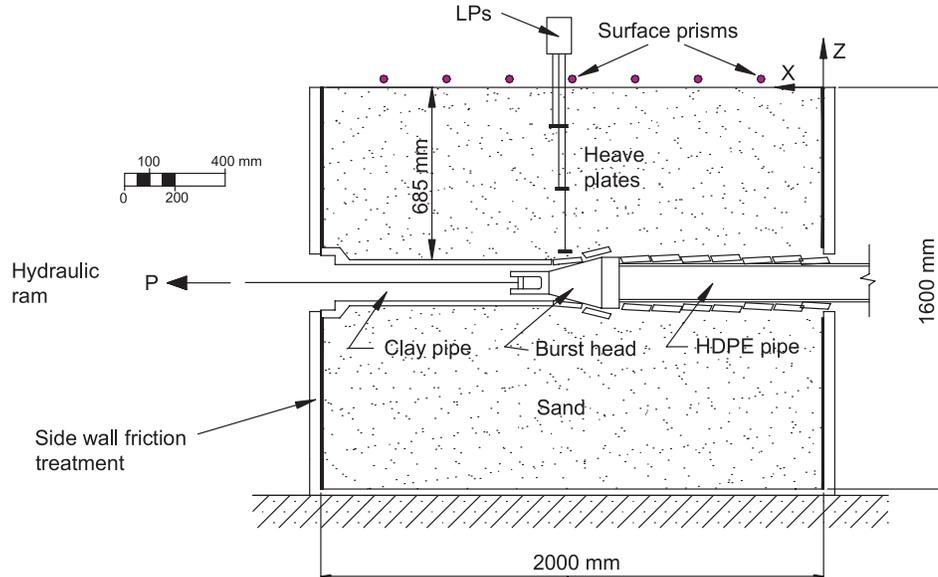
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Fig. 1. Cross-section through test apparatus showing the setup for the pipe burst experiment. P , pulling force.



equal to 10 mm) was used to replace existing clay pipes and was then subjected to vertical pressures up to 200 kPa applied at the ground surface.

Experimental details

The experiments were conducted using the apparatus developed by Brachman et al. (2001). Axial and transverse cross-sections through the apparatus are shown in Figs. 1 and 2, respectively, illustrating the configurations used during the bursting process and during the subsequent application of overburden pressures. The apparatus measures 2 m long by 2 m wide by 1.6 m deep. Vertical overburden pressures are simulated using a pressurized rubber bladder acting across the top surface. Horizontal stresses corresponding to zero lateral strain conditions are modelled since the stiff side walls of the soil box restrict the lateral movements of those boundaries to negligible levels.

The results from five experiments are reported. Four tests (Tests 1, 2, 3, and 6) involved replacing an intact clay pipe with OD = 184 mm and $t = 19$ mm with an HDPE pipe with OD = 165 mm and $t = 10$ mm. These experiments are referred to as replacement tests because the internal diameters of the existing and replacement pipes are essentially the same. The fifth experiment (Test 4), referred to as an upsize test, involved replacing a smaller intact clay pipe having OD = 128 mm and $t = 14$ mm, with the 165 mm OD HDPE pipe.

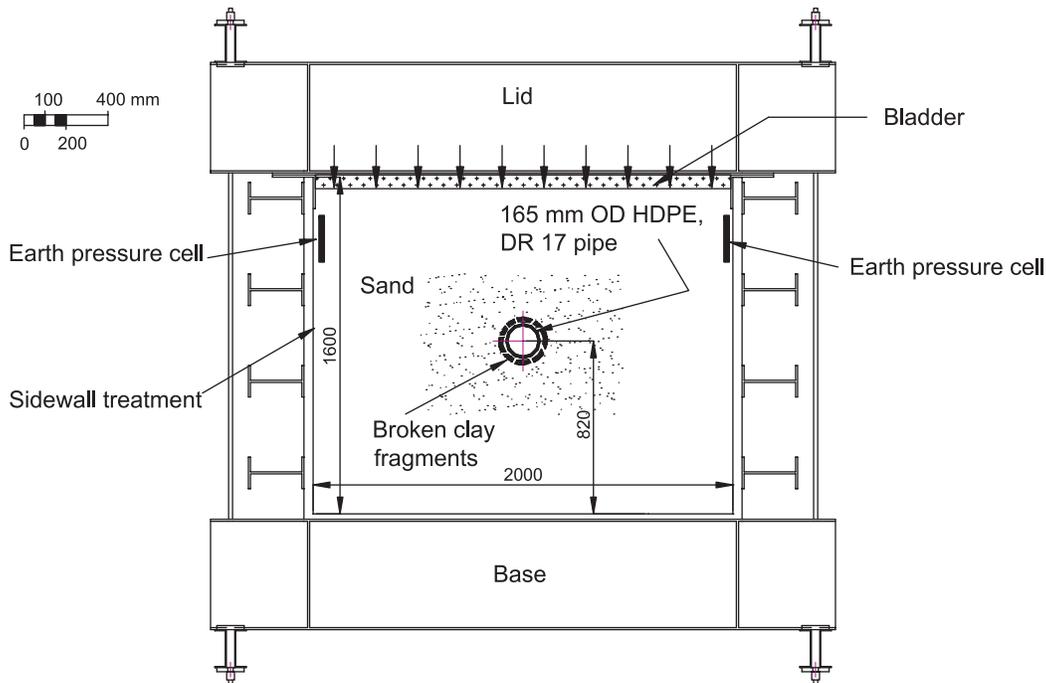
The laboratory procedures have been described in detail by Lapos (2004), and only a brief overview is given here. Prior to soil placement, the lateral boundaries of the apparatus were treated to reduce boundary friction. The treatment consisted of applying silicone grease between two 0.1 mm thick polyethylene sheets, which resulted in boundary frictions of less than 5° (Tognon et al. 1999). The clay pipe was placed near the centre of the apparatus and backfilled with a poorly graded sand, a synthetic olivine with a mean grain size of 0.5 mm. The sand was placed in 200 mm thick lifts, and each lift was compacted by dropping a 250 mm square plate with a mass of 6.8 kg a distance of 0.3–0.4 m.

The dry densities and water contents of the sand, which were measured using a nuclear density meter, are given in Table 1. The maximum and minimum dry densities for the sand in its densest and loosest possible states were 1.55 and 1.31 g/cm³, respectively, yielding an average density index of the sand after placement of 68%. The sand, at the density tested, has an internal angle of friction of 44° (Lapos and Moore 2002) and a one-dimensional secant Young's modulus (E_s) of 50–60 MPa for the range of overburden stresses examined in the tests. These values were calculated based on the measured vertical displacement of a settlement plate located 500 mm above the base and 400 mm from the lateral boundary (to obtain the vertical strain) and known applied vertical pressures (to obtain the vertical stress). This approach has been shown to provide values of Young's modulus that match those inferred from the pipe response (Brachman et al. 2001).

For the pipe bursting portion of the experiments, Tests 1, 2, 3, and 4 were conducted with sand up to the top of the apparatus (cover depth is equal to 685 mm), while Test 6 was conducted with 885 mm cover (the sand above the apparatus was supported with stiff but removable walls). Once the sand was placed to the required elevation, the HDPE pipe was pulled into place. A commercially available burst head with a maximum OD of 202 mm was used. The burst head had a sharp fin to fracture the clay pipe. The fin was initially oriented at the 12 o'clock position or crown of the clay pipe but was free to rotate during the experiment. A steel rod was attached to one end of the burst head to pull it through the clay pipe, while the HDPE pipe was attached to the other end. The force required to pull the HDPE pipe into place and the subsequent ground deformations from pipe bursting were recorded and have been reported by Lapos (2004).

The linear potentiometers (LPs) attached to heave plates and reflective prisms on the ground surface shown in Fig. 1 were used to monitor the ground movements during the bursting process (Lapos et al. 2004). These were removed following completion of the pipe burst procedures, and the

Fig. 2. Cross-section of the pipe test box (measurements in mm). DR, dimension ratio (equal to the diameter divided by the thickness, which is equal to 17).



sand was levelled to the top of the apparatus. The rubber bladder and apparatus lid were then installed to permit application of vertical pressure. The vertical pressure was applied in increments of 20 kPa every 12 min until a maximum vertical pressure of 200 kPa was reached.

Results

Pipe deflections

Pipe deflections were quantified by measuring the vertical (ΔD_v) and horizontal (ΔD_h) diameter changes of the pipe using LPs that were located at different axial positions along the centreline of the pipe (z). Deflections were measured to an accuracy of ± 0.01 mm. Measured values of ΔD_v and ΔD_h from Tests 1–3 are plotted in Fig. 3 for the replacement tests with a cover of 685 mm. Deflections were measured at one section located at $z = 50$ mm (where z is the axial distance from the centre of the pipe) for Tests 1 and 2, while measurements were made at four sections (± 50 and ± 100 mm from the pipe centre) for Test 3. The relatively close spacing of the measurements was intended to investigate any local variations in deflection resulting from interaction with the remnants of the clay pipe.

As expected, the results in Fig. 3 show that the pipe experiences a general decrease in vertical diameter (i.e., negative diameter change) and an increase in horizontal diameter when subjected to an increase in vertical pressure. However, the development of pipe deflections during these tests differs from previous experiments with similar HDPE pipes that did not involve pipe bursting. For example, most of the measurements in Fig. 3 show very small deflections to 80–100 kPa, which subsequently increased at larger pressures, whereas experiments undertaken on HDPE pipe buried directly in sand in a conventional manner produce essentially linear and monotonic increases in deflection with pressure (e.g., see

Table 1. Summary of test configurations.

		Cover to clay pipe (mm)	Clay pipe OD (mm)	Gravimetric water content of sand (%)	Dry density of sand (g/cm^3)
Test 1	R	685	184	3.15	1.49
Test 2	R	685	184	4.40	1.44
Test 3	R	685	184	3.50	1.47
Test 4	U	685	128	3.95	1.46
Test 6	R	885	184	3.27	1.47

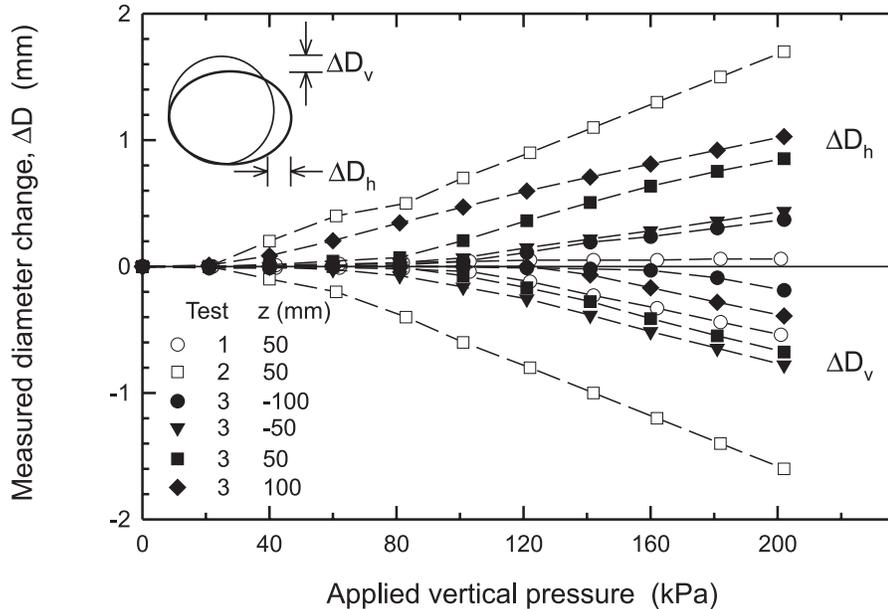
Note: R, replacement; U, upside; OD, outside diameter.

Brachman et al. 2001). The effect on the soil due to the cavity expansion and contraction processes associated with pipe bursting and (or) the effect of the remnant clay fragments are possible explanations for the observed delay or offset in pipe response. Deflections from Test 2 appear to commence at lower pressures than those for Tests 1 and 3. As discussed later in the paper, this is believed to occur as a result of differences in interactions with the remnant clay fragments.

The deflections are much more variable for the pipe installed using pipe bursting than previous experiments conducted without pipe bursting. The vertical diameter change varies between -0.2 and -1.5 mm at 200 kPa for Tests 1–3, as shown in Fig. 3. Without pipe bursting, measured deflections at duplicate sections were essentially identical for similar sand backfill (Brachman et al. 2001). The variations observed in Fig. 3 are possibly due to the presence of clay fragments around the pipe.

Despite the measured variations, the vertical diameter change from Test 1 lies within the range of values from Test 3, as expected for identical experimental conditions. Although the three experiments were conducted in essen-

Fig. 3. Measured vertical and horizontal diameter changes from replacement Tests 1, 2, and 3.



tially the same manner, the measured deflections from Test 2 are larger, and they begin to increase at a lower vertical pressure than those recorded during Tests 1 and 3. Visual observations presented later in the paper indicate that the differences in pipe deflections between Tests 1 and 3, and Test 2 arise from the nature of the broken fragments of the original clay pipe.

Figure 4 shows the measured ΔD_v during Test 6 (the same as Tests 1–3 but with pipe bursting conducted at a cover of 885 mm). The vertical diameter change was measured at six axial locations ($z = 60, 100, 160, 210, 270,$ and 300 mm from the centre of the pipe) to better quantify the variable response of the pipe. These potentiometers were installed after the pipe was pulled in place to verify that the pipe bursting process did not affect the operation of the instrument; however, this approach precluded measurement of ΔD_h in this test. These results show a similar delay in pipe response as that found in Tests 1 and 3. The magnitude of deflections from Test 6 lies within the scatter of Tests 1 and 3, even though the cover depths were different during the bursting operation. This is likely a result of the magnitude of the final increase of vertical pressure being greater than 50 times larger than the additional burial depth of 200 mm employed in Test 6.

Measured values of ΔD_v and ΔD_h from the upsize Test 4 are plotted in Fig. 5. The vertical diameter change varies between -0.9 and -1.5 mm at 200 kPa. These measured deflections for Test 4 are larger than those for Tests 1, 3, and 6 but are similar to the results from Test 2. The deflections for Test 4 start to increase at an applied pressure between 20 and 40 kPa.

Broken clay pipe

Observations recorded during and subsequent to the experiments are now considered to examine the influence of the remnant clay pipe fragments on the response of the pulled-in-place HDPE pipe.

First, during replacement Tests 1, 3, and 6, cracking sounds originating from inside the test apparatus could be heard once the vertical pressure was applied. It is believed that these sounds were produced by movements along contacts among clay fragments. The cracking sounds were more pronounced during the initial 5 min of each load increment between 0 and 100 kPa. After 100 kPa, the cracking sounds were less frequent. When the vertical pressures reached 180 kPa, no sounds were heard during any replacement test. It was interesting to notice that upsize Test 4 produced no audible sounds during any load increment in overburden pressure.

Second, upon completion of each experiment, the soil was exhumed by hand down to the pipe level to permit a detailed study of the size and orientation of the fragments of broken clay pipe. Pressurized air was blown on the pipe to remove the final particles of sand and reveal the position of the broken clay fragments without disturbing their orientation. Photographs presented in Figs. 6–10 were taken following excavation of Tests 1, 2, 3, 6, and 4, respectively.

The fracture patterns observed in Tests 1, 3, and 6 are similar. For these experiments, the broken clay fragments were in contact with each other at many locations along the pipe. It was observed that sand filled the gaps among clay fragments. It is hypothesized that at low applied pressures, the clay fragments that are in contact with one another are able to sustain some load. The load acting on the HDPE pipe thus remained small, and there was little deflection of the HDPE pipe. As applied vertical loading increased, the clay fragments began to move relative to each other, allowing transfer of the load to the HDPE pipe. It appears that variations in measured deflections arise from the variable contact conditions among fragments.

The fracture pattern observed in Test 2 (Fig. 7) differs from that observed in Tests 1, 3, and 6. A pronounced crack (approximately 890 mm long and 30–35 mm thick) was observed along the crown of the clay pipe. The crack was filled

Fig. 4. Measured vertical diameter change from replacement Test 6.

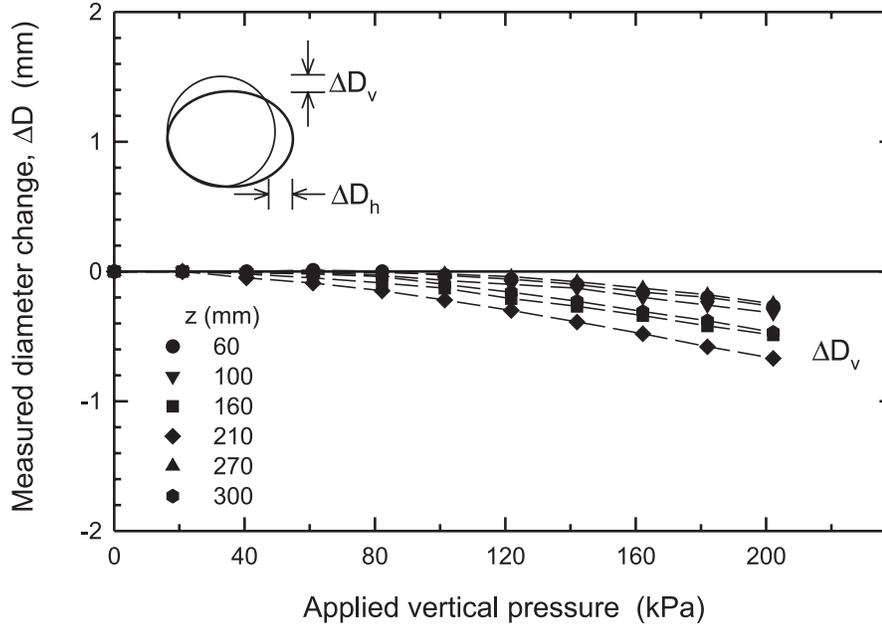
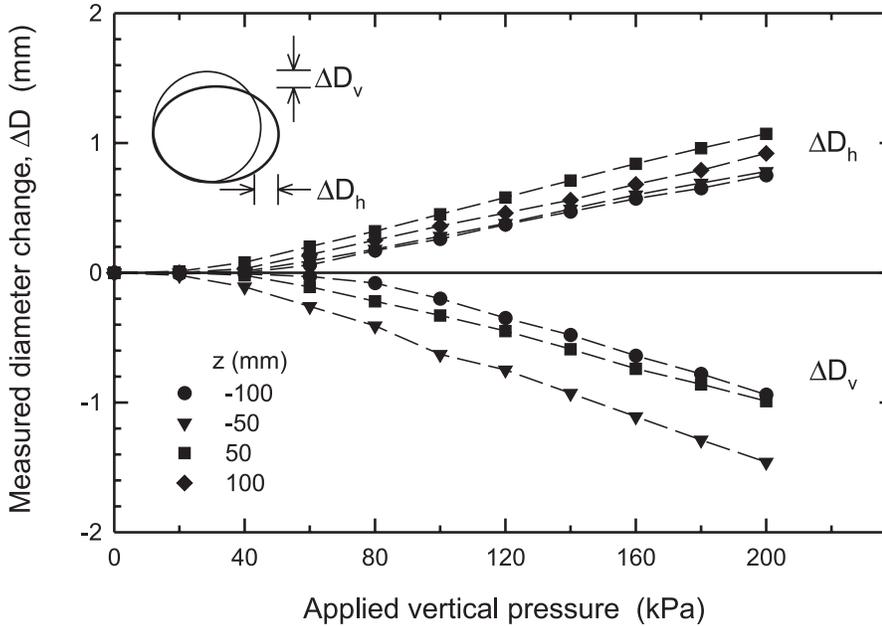


Fig. 5. Measured vertical and horizontal diameter change from upside Test 4.



with sand, preventing direct contact among the clay fragments above the HDPE pipe. This reduced contact among the broken clay fragments appears to have led to greater loads reaching the pipe (relative to Tests 1, 3, and 6) and hence larger pipe deflections (as seen in Fig. 3). Expansion and contraction of the initial soil cavity may also change the density of the soil in the vicinity of the pipe. The soil density is difficult to quantify, but may allow the pipe to settle within the newly expanded and contracted soil cavity. This may also contribute to a delay in the vertical pressure reaching the pipe. Reduced contact among fragments and changes in soil density around the pipe likely explain the reduced offset in deflections for Test 2 relative to Tests 1, 3, and 6, as previously discussed with respect to Figs. 3 and 4.

A photograph of the broken clay pipe fragments for upside Test 4 is shown in Fig. 10. The broken clay fragments produce different fracture patterns than those seen with the replacement experiments. Unlike the replacement experiments, the clay pipe fragments do not encase the HDPE pipe, and consequently do not provide additional hoop strength. The smaller clay pipe was broken into much smaller fragments that were displaced radially away from the HDPE pipe, suggesting that the clay pipe could not provide any additional hoop strength. No audible sounds were heard during vertical pressure increase, supporting the hypothesis that no interaction of clay fragments occurred. When there is no interaction among the clay fragments, the delay in measured diameter change appears to arise as a

Fig. 6. Fracture conditions, Test 1.**Fig. 7.** Fracture conditions, Test 2.

product of the expansion and subsequent contraction of the soil cavity around the pipe during the pipe bursting process. The development of shear failure in the soil surrounding the clay pipe likely led to soil dilation, hence the soil was loosened compared to its density after the test preparation. The soil that initially surrounds the clay pipe (184 mm OD) is compressed by the action of the burst head (202 mm OD). After passage of the burst head, the soil is then forced back around the new HDPE pipe (165 mm OD) by the self weight of the overlying soil, however, it is in a loosened state compared to the initial conditions. Recompression of this loosened sand around the new HDPE pipe explains the small delay in measured diameter change for this test, even though the clay fragments surrounding the HDPE pipe were not in contact.

Fig. 8. Fracture conditions, Test 3.

Interaction among sand, clay pipe, burst head, and HDPE pipe

The likely radial deflection of an arbitrary soil ring just outside the clay pipe is illustrated in Fig. 11 for different stages of the experiment. Figure 11*a* shows the location of the ring after backfilling but prior to pipe bursting. As the burst head breaks and passes through the clay pipe, the ring deforms outward as shown in Fig. 11*b*. These types of deformations have been assessed by Rogers and Chapman (1998) and Nkemitag (2007). The fragments of the clay pipe also deform radially outwards, and sand most likely fills the spaces among fragments. Figure 11*c* shows that once the burst head passes, there would be some radial compression of the soil ring because the diameter of the burst head (202 mm) is larger than that of the pulled-in-place pipe (165 mm). A ring of sand was observed between the broken clay pipe and the HDPE pipe, which rained in as a result of its self weight and the weight of the overlying sand. Once additional vertical pressure is applied with the rubber bladder (Fig. 11*d*), the ring may experience little compression depending on the contact among the remnant clay fragments. The sand between the clay pipe fragments and the HDPE pipe may also compress, resulting in contraction of the soil ring, but not necessarily of the pipe. As the applied pressures become larger, the soil ring would decrease its vertical diameter and increase its horizontal diameter, following the deformations of the new plastic pipe.

Practical implications

It is clear from Fig. 11 that the potentially complex interactions among the fragments of replaced pipe, the replacement pipe, and the backfill soil, and the effect on the soil due to its expansion and subsequent contraction, make quantification of pipe deflections a challenging task. It is of interest to see how well the measured results compare with calculated deflections assuming that the pipe was not installed by pipe bursting, but rather, buried in a conven-

Fig. 9. Fracture conditions, Test 6.**Fig. 10.** Fracture conditions, Test 4.

tional manner within an embankment or wide cut-and-cover trench.

Table 2 presents a comparison of the measured deflections (arithmetic mean and 95% confidence interval, CI) at 200 kPa with those calculated using the elastic continuum solution of Hoeg (1968). This solution considers a pipe surrounded by backfill soil and subjected to vertical and horizontal earth pressures that act distant to the pipe. In this approach, the soil is treated as linear elastic material. Secant values of Young's modulus, E_s , of 50 and 60 MPa corresponding to the inferred one-dimensional confined modulus and lower values of 30 and 40 MPa were considered. The lateral earth pressure coefficient, K_0 , was taken to be 0.2 based on measured changes in horizontal earth pressure (Lapos 2004), and Poisson's ratio, ν_s , was taken to be 0.17 to provide this K_0 based on one-dimensional elastic compression.

Table 2. Summary of measured and calculated pipe deflections.

	ΔD_v (mm)		ΔD_h (mm)	
	Mean	$\pm 95\%$ CI	Mean	$\pm 95\%$ CI
Measured				
Test 1	-0.5	—	0.1	—
Test 2	-1.6	—	1.7	—
Test 3	-0.5	0.3	0.7	0.3
Test 6	-0.4	0.1	—	—
Test 4	-1.1	0.3	0.9	0.1
Calculated				
$E_s = 60$ MPa	-0.9		0.4	
$E_s = 50$ MPa	-1.0		0.5	
$E_s = 40$ MPa	-1.2		0.6	
$E_s = 30$ MPa	-1.6		0.9	

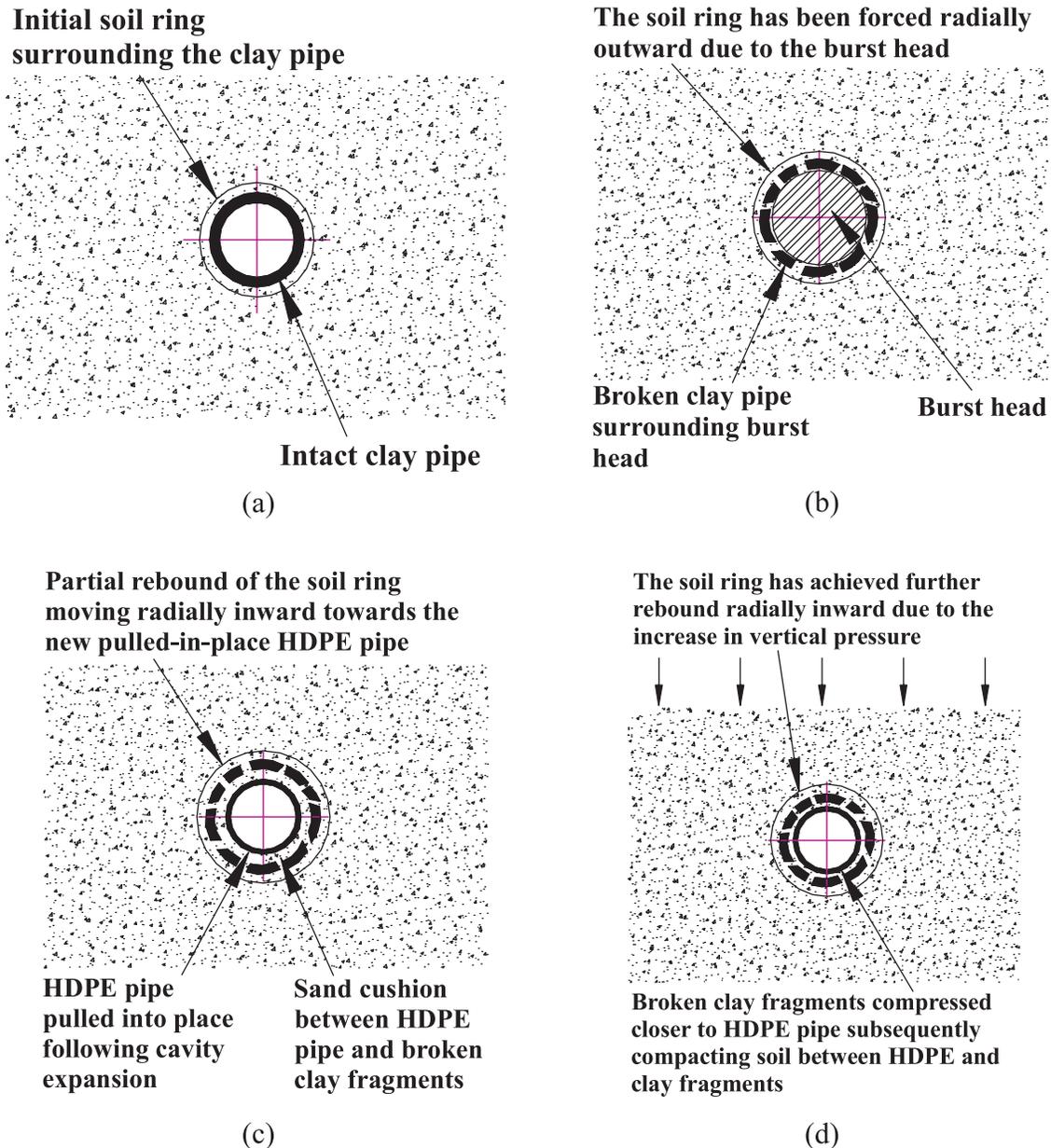
The HDPE pipe was modelled as linear elastic with $E_p = 400$ MPa and $\nu_p = 0.46$. Although HDPE demonstrates a nonlinear, viscoplastic stress-strain response (Zhang and Moore 1997), linear elasticity may be used to quantify its response under loading provided an appropriate secant modulus is used. The values used in this assessment were selected for the particular strain rate and time of the test from the constitutive model developed for this particular pipe material by Zhang and Moore (1997). The interface between the pipe and sand was assumed to be fully bonded.

For the tests where the clay pipe fragments appeared to delay the onset of HDPE pipe diameter change under applied pressure (i.e., Tests 1, 3, and 6), the mean vertical diameter change is -0.5 mm at 200 kPa. This is only one-half of the calculated value in Table 2 with $E_s = 50$ MPa. The interactions among clay fragments provide additional hoop stiffness around the HDPE pipe, and consequently, the measured deflections are less than the theoretical values, which neglect the contribution of the clay pipe fragments to the system stiffness.

For replacement Test 2, which showed no signs of additional stiffness or restraint provided by the broken clay fragments, the measured vertical diameter change exceeds the calculated values using the inferred one-dimensional confined modulus in Table 2 by 60%. It is possible that the expansion and subsequent contraction of the soil around the pipe leads to larger diameter changes because of the lower stiffness of the soil directly around the pipe. If the soil modulus is reduced to 30 MPa, in an attempt to reflect lower stiffness around the pipe, the calculated value of ΔD_v provides a much better match to the measured value. While this approach does not fully capture the mechanics of the problems (ΔD_h is still underestimated), it does capture the maximum diameter change that would govern design for the particular conditions tested.

The average measured deflections from Test 4 are only slightly greater than the calculated value in Table 2 with $E_s = 50$ MPa. There appears to be no additional hoop stiffness provided by the broken clay fragments, which is consistent with the post-test visual inspection. Overall, the measured deflections of the HDPE pipe are small and are less than 1% of the pipe diameter at 200 kPa. This is

Fig. 11. Progression of a ring of soil surrounding the intact clay pipe. (a) Initial setup. (b) Soil cavity expansion due to the burst head. (c) Partial rebound of the soil. (d) Application of vertical pressure.



much smaller than the allowable 4% diameter change specified in ASTM F714 (ASTM 2001) for the particular diameter to thickness ratio of the pipe tested.

Conclusions

Measured deflections of an HDPE pipe (OD = 165 mm, $t = 10$ mm) installed by pipe bursting (replacing an intact clay pipe buried in sand) and then subjected to overburden pressures were reported. Expansion and subsequent contraction of the surrounding soil during the pipe bursting process and interaction among fragments of the broken clay pipe were found to influence the deflections of the new HDPE pipe.

In three of the four replacement tests (clay and HDPE pipes have the same internal diameter), the broken clay frag-

ments were observed to be in contact with each other at many locations along the pipe. Interaction among these fragments resulted in a delay in HDPE pipe deflection (with little to no deflection up to 80–100 kPa) and produced smaller pipe deflections at 200 kPa than if the HDPE pipe was just buried in sand (i.e., no clay pipe or pipe bursting). In these cases, an elastic continuum solution that neglects the presence of the clay fragments conservatively overestimated the maximum measured HDPE pipe deflection.

In one replacement test, contact among the broken clay fragments was prevented as gaps filled with sand developed among the fragments. The HDPE pipe deflections were larger in this case than for those just buried in sand. This indicates that the stiffness of the sand surrounding the pipe has decreased because of the expansion

of the soil and its dilation during the pipe bursting process. The maximum vertical diameter change could only be captured using the elastic continuum solution when the elastic Young's modulus of the sand was reduced to one-half of the one-dimensional secant Young's modulus measured for this sand in its undisturbed state. This simple reduction of modulus in design may be suitable for projects where the consequences of unacceptable performance are low. At present, laboratory testing such as that reported in this paper would be preferable for the design of projects where the consequences of unacceptable performance are significant.

Although large variations in pipe deflections were measured during both the replacement and the upsize experiments, the measured diameter change remained small for the maximum overburden pressure of 200 kPa examined, producing a vertical maximum diameter change of less than 1% and an average diameter change of less than 0.5% of the original pipe diameter.

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